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RESEARCH ARTICLE

A comparison of farm-level greenhouse gas calculators in their application on beef production systems

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Abstract

Farm-level greenhouse gas (GHG) footprinting tools produce markedly different results from common input datasets. These tools are typically empirical, broad scope models which are valuable for their ability to account for a range of on-farm GHG sources using non-specialist data. Many of these tools are publicly available, and are employed by users from a range of backgrounds to provide enterprise-level carbon footprints. They may be used to inform mitigation strategies and policy developments, though are often developed outside the peer-review system, and as such the methodology employed may be sparsely documented.

The study reported here rigorously tests these tools and discusses differential findings. Five farm-level tools were tested using data from a variety of beef production enterprises. Beef production was chosen as an emissions intensive form of livestock production, and the focus of considerable mitigation effort globally. Considerable inconsistencies between tools were found in the resulting estimates.

Estimates of emissions stemming directly from livestock were variable, and the largest contributor to the overall farm footprint (43 – 92% of total). As such, consistent calculation of these emissions is of considerable importance. Similar variability was found in other emissions categories. The emissions intensity of beef production was calculated for each estimate and compared to published values from LCA literature. Some tools produced estimates concurrent with these values, whilst others markedly underestimated in comparison.

This study highlights the differences between estimates produced by these tools, and explores the reasons behind them. Of relevance to users is the finding that even where farm-level estimates appear similar between tools, the composition of these estimates can vary. As such, different tools respond differently to system changes. In highlighting and exploring the impacts this can have, the conclusions of this study provide a key reference point for tool users and developers.

Keywords: carbon calculator, carbon footprint, farming systems, beef production, livestock, greenhouse gas

1. Introduction and rationale

Agriculture in the UK was responsible for the emission of 48 Mt CO_2-eq in 2008, a contribution of 8% to national emissions (Comittee on Climate Change, 2010). Under the Climate Change Act 2008, the UK Government is committed to reducing national emissions to 20% of 1990 levels by 2050; UK agriculture is correspondingly required to achieve a 34% reduction by 2020 (Comittee on Climate Change, 2008). This commitment in the UK follows international climate commitments; the EU Roadmap recommends a reduction in European agricultural emissions of 36-37% for 2030, and 42-49% for 2050 (Domingo et al., 2014).

Moran et al. (2011) show that to achieve this target will require considerable mitigation effort within the agricultural sector. The livestock sector contributes substantially to agricultural emissions and hence is likely to come under detailed scrutiny. Quantifying and mitigating for GHG emissions from livestock is therefore of considerable policy importance on both national and international scales. Whilst quantification of farm-level emissions is not straightforward, it is a crucial step towards cleaner agricultural production (Yan et al., 2015).

A number of tools, developed in a variety of contexts, are available to assist with this process (Colomb et al., 2012). By providing a quantitative assessment of farm-level emissions, these tools perform a crucial role in facilitating reduction in the environmental impact of production. Some, such as the Cool Farm Tool (Hillier et al., 2011) have been developed within the academic sector; others such as CPLANv0 (SEE360, 2007) have been developed by businesses for consultancy-oriented purposes. Others, such as the CALM tool (CLA, 2009) are developed by not-for-profit organisations.

Hall et al. (2010) reviewed three UK-specific farm GHG accounting tools with the aim of recommending a single tool for promotion by the Scottish Government. However, the authors found that a qualitative approach was insufficient to recommend a single tool for this purpose. A lack of consensus in GHG accounting methods, together with lack of available information on tools was a key reason for this conclusion.

Without this consensus in place, each tool employs a unique range of methodologies, and the scope of assessment varies. This may be the product of the context in which a tool was developed; Colomb et al. (2012) note that this factor is likely to affect the depth and scope of a tool. Furthermore, the requirement to combine methodologies, inherent in the nature of such broad-scope models, is likely to further exacerbate differences. Some methodologies, such as the IPCC (2006) Guidelines, were not specifically intended for farm-level calculations, and so the necessary adaptation of these may act as further basis for disparity. Whittaker et al. (2013) found that tool transparency is often insufficient to shed light on the decisions made whilst adapting these methodologies.

In order to gain further insight into these issues, several studies have included quantitative analyses of these tools. These studies test tools in the context of the cultivation of palm oil and sugar cane (Keller et al., 2014), wheat in the United Kingdom (Whittaker et al., 2013), and a variety of European cereal cultivation scenarios (Lewis et al., 2013). All highlight disparities between tools in terms of scope, boundaries, and results. However, whilst illuminating in many respects, these studies have been limited in that all concern only arable enterprises. Given the contribution of livestock to agricultural emissions both in the United Kingdom (Moran et al., 2011) and further afield (Xu and Lan, 2016), coupled with the relative complexity of livestock systems (Schils et al., 2007) and the recognised issues with many available tools, the requirement for an empirical assessment of these tools on representative livestock enterprises is increasingly apparent.

This study aims to provide a reference point for prospective tool users in selecting a tool for their purposes, and for developers in further improving the tools. Tools of this type have proven potential in facilitating environmentally efficient agricultural production (e.g. Hillier et al., 2011), but the evidenced methodological variation and lack of accompanying information for many tools (Whittaker et al., 2013) means that users require further insight in order to realise this potential. Such an assessment must follow a critical, quantitative approach in order to provide maximum insight, and this study seeks to fulfil that requirement through a quantitative comparison of tool estimates based on a representative range of UK livestock enterprises. The relevance of such an approach is heightened by the importance of livestock production in both agricultural and national-level GHG budgets. Robust conclusions are sought as to the consequences of existing differences in accounting methods on the final farm-level footprint, and on corresponding implications for users and policy makers.

2. Methodology

2.1. Calculator selection

Farm-level carbon accounting tools were selected for review based on pre-determined criteria, defined as follows:

Tools had to be greenhouse gas calculators applicable to the livestock industry and specific to the agricultural sector. Data constraints (Section 2.3) meant that tools had to be, if not UK-specific, at least UK applicable. Additionally, it was determined that tools must be publicly available without cost, and must function at farm-level.

Tools were sourced via web searches and from previously completed reviews, specifically Colomb et al. (2012) and Whittaker et al. (2013). Five tools were identified as complying with the above criteria and were selected for review (Table 1). These are described below. No suitable tools were knowingly rejected from the sample. Table 2 provides a summary of tools' scope and system boundaries.

Table 1. Farm-level GHG accounting tools chosen for review.

Name	Developer	Type	Website
AgRE Calc	SAC Consulting	Online	www.agrecalc.com
Cool Farm Tool	Cool Farm Alliance	Online/Excel download	www.coolfarmtool.org
CALM	Country Land & Business Association (CLA)	Online	www.calm.cla.org.uk
CPLANv0	See360 Ltd.	Online	www2.cplan.org.uk
CFF Calculator	Climate Friendly Food	Online	www.cffcarboncalculator.org.uk

2.1.1. *AgRE Calc*

AgRE Calc (SRUC, 2014), standing for Agricultural Resource Efficiency Calculator, was developed by the consulting division of Scotland's Rural College. The tool forms part of the organisation's consultancy services, though is freely available for non-commercial use.

IPCC (2006) Tier II calculations are employed to calculate livestock and manure management emissions. Emissions from production of fertilisers and pesticides ('embedded' emissions) are calculated using Carbon Trust (2010) emission factors, whilst N_2O emissions from fertiliser and crop residues follow IPCC (2006) Tier I methodology. The tool also calculates embedded emissions for imported feed and bedding, based on emission factors (EFs) from Kool et al. (2012).

Electricity, renewable energy and fossil fuel emissions are calculated using emission factors from DEFRA/DECC (2011) Conversion Factors for Company Reporting. Finally, carbon sequestration from woodland is calculated using IPCC (2006) methodology at Tier I level. The online tool is certified under the PAS2050:2011 specification for GHG life cycle assessment (BSI, 2011).

2.1.2. *The Cool Farm Tool*

The Cool Farm Tool (Hillier et al., 2011) was developed at the University of Aberdeen and is freely available under a creative commons licence. Hillier et al. (2011) state that the tool was designed to function at an intermediate level; requirement for high levels of data input was avoided, but provision for data input beyond the standard Tier I inventory methods (IPCC 2006) were included, providing insight on a local scale. The tool is unique in this sample in that the methodology has been published in peer-reviewed literature (Hillier et al., 2011) where the development of the Cool Farm Tool is described. The EcoInvent emission factor inventory (Ecoinvent Centre, 2007) was used to provide EFs for fertiliser production and renewable electricity usage. Hillier et al. (2011) incorporated a model developed by Bouwman et al. (2002) to determine N_2O emissions relating to fertiliser usage. IPCC (2006) methodology was used for livestock and manure emissions. Hillier et al. (2011) state that the model can perform Tier I or Tier II level calculations, as allowed by input data. The tool is not PAS2050 certified, though has been extensively reviewed in academic and non-academic literature.

2.1.3. The CALM Calculator

The CALM Carbon Calculator was developed by the Country Land and Business Association, in partnership with Savills (CLA 2009). The model methodology is described as following that used in the most recent National Inventory Report.

Model methodology assesses N_2O emissions from crop residues, fertiliser and manure management. Methane emissions from enteric fermentation and manure management are calculated. Embedded emissions from synthetic fertiliser and lime are assessed, as are emissions associated with on-farm fuel and electricity use. The model can also assess sequestration from forestry, soil organic carbon and land use change. Embedded emissions associated with purchased feed and bedding are not assessed. The tool appears to draw on methodology from the IPCC Guidelines for emissions from livestock and manure (Dong et al., 2006) and land management (de Klein et al., 2006), and the UK GHG inventory (DEFRA/DECC, 2013), though is not PAS2050 certified.

2.1.4 – CPLANv0 Calculator

CPLANv0 (SEE360 2007) is a free-to-use carbon calculator which forms part of a consultancy business. The development was supported by public funding. The model forms a key component of the agricultural consultancy business SEE360 Ltd.

CPLANv0 forms the basis for CPLANv2, a more detailed calculator which is not free to use. Other than the statement that IPCC (2006) methodology has been observed, there is little detail given as to the methodology of the CPLANv0 calculator. The system boundaries include CH_4 from enteric fermentation and manure. Nitrous oxide from crop residues and fertiliser is assessed. Emissions from fossil fuel and electricity use are also included. The sequestration potential of standing woodland is assessed, as well as impacts from forestry and land use change. The tool is not PAS2050 certified.

2.1.5 – CFF Carbon Calculator

The Farm Carbon Calculator (CFF Carbon Calculator, 2012) is a not-for profit online tool which places a strong emphasis on organic agriculture. The livestock section of the model appears to be based on standard Tier I methodology (IPCC, 2006), though this is not specifically stated.

The model has the capability to assess GHG emissions from fuel and electricity use, material consumption, crop production/importation, fertiliser use, enteric fermentation and manure management.

There is the facility to assess emissions associated with building materials and capital items such as farm machinery. There are functions to assess post farm gate haulage emissions, and to assess carbon sequestration by woodland, orchards, hedges and field margins.

Little emphasis is placed upon N_2O emissions (Whittaker et al., 2013). Where these are associated with crop residues, they are considered in the model; however, the calculations take no account of N_2O emissions from fertiliser spread or from manure. The tool as a whole does not hold PAS2050 certification.

Table 2. Summary of emissions sources included by the tools. Note that this table is not intended as an exhaustive list of farm-level emissions sources, but is tailored to the tools and input data. *Y* = included, *N* = not included, *?* = unclear.

		AgRE Calc	**Cool Farm Tool**	**CALM**	**CPLAN v0**	**CFF**
Crop residues	**N_2O**	Y	Y	Y	Y	Y
Manure application	**N_2O**	Y	Y	Y	Y	N
Fertiliser application	**N_2O**	Y	Y	Y	Y	N
Lime/urea application	**CO_2**	Y	Y	Y	Y	N
Manure management	**CH_4**	Y	Y	Y	Y	Y
	N_2O	Y	Y	Y	Y	N
Enteric fermentation	**CH_4**	Y	Y	Y	Y	Y
Fertiliser	**(embedded)**	Y	Y	Y	?	Y
Feed	**(embedded)**	Y	Y	N	N	Y
Bedding	**(embedded)**	Y	Y	N	N	N
Pesticides	**(embedded)**	Y	Y	N	N	Y
Plastics	**(embedded)**	Y	N	N	N	Y
Diesel	**CO_2**	Y	Y	Y	Y	Y
Electricity	**CO_2**	Y	Y	Y	Y	Y

Woodland (sequestration)	**CO_2**	Y	Y	Y	Y	Y

2.2. Data acquisition

Sample data for seven farms was sourced from within the repository of Scotland's Rural College (SRUC); these represented a mix of SRUC-owned farms and independent affiliated enterprises from different regions across Scotland. In selection, emphasis was placed on beef production; this in part reflects the high environmental impact of beef as compared to other livestock enterprises (Eshel et al., 2014), and provides a link between each of the farms for comparison of emissions intensity.

The farms nevertheless contained a mix of additional enterprises, and are summarised below, with Table 3 presenting the standing herds and output from each enterprise.

Farm A comprised of a total of 1,015 ha, with 939 ha a mix of hill, upland and lowland grazing. Arable crop production on the remainder partially supplied the feed requirements of the livestock. The farm ran cattle in a breeder/store system with 200 suckler cows, and a mixed hill and lowland sheep system with 1,200 ewes.

Farm B produced winter wheat, winter barley, spring barley and oats on 242 hectares of land. An additional 282 hectares were under grass to support the beef enterprise, which comprised a herd of 300 Limousin cross suckler cows, with all progeny finished on the farm.

Farm C had a large dairy herd with around 250 milking cows. A smaller beef enterprise drew on the dairy herd, and a flock of 312 ewes produced 500 lambs for sale annually.

Farm D comprised a suckler beef unit of 100 cows, and a sheep unit of around 300 ewes which produced around 500 lambs for sale annually. A large pig unit of comprising approximately 650 adults and 2,000 juveniles was also present. Around 92 hectares of crops were grown to support the livestock enterprises.

Farm E was an upland beef and sheep farm, comprising a beef herd with 140 suckler cows, and two sheep flocks comprising 800 ewes in total. Around 8 hectares of land was used to grow forage crops to support the livestock enterprises.

Farm F was a 329 hectare organic dairy farm comprising a herd of 170 dairy cows. The business retained all of the offspring from the dairy herd, and finished around 100 head of cattle for beef annually. Additionally, 56 hectares of land was devoted to arable production, supporting the livestock enterprises.

Farm G comprised a flock of around 250 Dorset cross ewes, 30 mixed breed suckler cows and a varying number of finishing cattle bought as stores or weaned dairy calves from other organic units. Around 20 hectares of cereals were grown to provide winter feed for the livestock. Livestock were finished on farm.

Carbon footprinting data characterising these farms was collected by SAC Consulting for calendar year 2014, except for farms E and F, where data availability necessitated the use of 2013 data. Boundaries for system characterisation were cradle to farm gate (see Section 2.3 for further details).

Table 3. Annual herds, land areas and outputs for farms A – G, based on the sample data. The values given in head (Hd) refer to the average number over the footprint year, and hence reflect a) the individual year in question, and b) the proportion of the year spent on the system by each livestock category.

			Farm A	**Farm B**	**Farm C**	**Farm D**	**Farm E**	**Farm F**	**Farm G**
Beef Cattle	Cows	Hd	266	274	8	100	146		28
	Bulls		5	7	1	4	6		1
	Heifers		116	213	17	133	108	64	48
	Steers/Male entire[1]		222	199	22	63	57	143	79
Sheep	Rams	Hd	42		26	10	34		12
	Ewes		1,203		312	310	783		265
	Juvenile		948		94	168	600		40
	Lambs		900		240	294	644		300
Dairy Cattle	Cows	Hd			257			173	
	Bulls				1			2	
	Heifers				149			139	
	Steers				38				
Pigs	Adult	Hd				659			
	Juvenile					2,080			
Land	Rough Grassland	Ha	622	7.3		24.1	788	35.1	128.2
	Improved Grassland		314	173.3	194.2	145.8	188	184.6	78.4
	Arable		49.7	243.3	54.6	91.9	8	55.9	19.8
	Woodland		11.8		16.2	30.1	33.3	51.4	80.8
Sales	Beef Suckler Cows	kg LW	17,342	34,104	1,300	7,700	12,826		
	Beef Bulls		1,500			1,250	1,044		

Beef Heifers		77,803	49,579	1,500	20,376	19,494	39,078	9,680
Beef Steers		77,803	69,687	3,120	24,050	27,813	29,880	26,000
Beef Male Entire[1]		3,960	21,000					
Ewes		19,800		1,440	3,975	18,200		3,740
Rams	kg LW	425		0		300		255
Lambs		41,589		23,000	24,940	55,440		10,955
Dairy Cows				3,404			18,690	
Dairy Bulls	kg LW			650			565	
Dairy Male Entire[1]				118,750				
Sows					2,322			
Boars	kg LW				230			
Finishing Pigs					814,200			
Wool	t	4.72		0.83	0.71	3.19		0.78
Milk				1,978			1,315	
Barley			921					
Oats			86					
Wheat	t		461		524			
Oilseed Rape					56			

[1] The male entire categories refer to uncastrated juvenile male dairy/beef cattle.

2.3. Data Preparation and Processing

The following data categories were supplied for each farm by the raw datasets:

- Land use category and area
- Arable yields by crop type
- Fertiliser and pesticide usage, type and application rates
- Livestock age, class and performance data
- Livestock feed types, quantities and provenance
- Manure management system types and usage
- On farm electricity and fuel use (at enterprise level)

To provide a baseline for comparison of outputs from the different models, manual estimates were calculated for emissions stemming directly from livestock (CH_4 enteric fermentation and N_2O manure deposition and management). This was done according to Tier I and II level methodology as specified in the IPCC (2006) Guidelines.

Summarising the approach, Tier I manual calculations used default emission factors for Western Europe for emissions from both enteric fermentation and manure. By contrast, the Tier II calculations followed the energy-based calculations as stipulated by the Guidelines, and made use of all activity data present in the sample datasets. Additionally, an online database resource, Feedipedia (INRA, 2012) was used to provide data for calculating the digestible energy and crude protein in the diet (DE% and CP%) at enterprise level, a required input for Tier II level calculation.

An emissions intensity estimate, in kg CO_2-eq / kg beef Live Weight (LW), was derived from the farm level results. In order to calculate this, it was necessary to allocate the emissions which formed the whole-farm estimate to different enterprises on the farms. However, with the exception of AgRE Calc, none of the sampled tools allocate emissions within the farm footprint.

AgRE Calc contains integrated protocols for the allocation of emissions to the end user enterprise wherever resource transfer (such as the provision of home-grown feed to livestock) occurs on farm.In the case of co-production (such as cereal grain and straw), allocation of emissions to products is based on economic value. For AgRE Calc, emissions as calculated for the beef enterprise were utilised. For estimates from other tools, in the absence of an integrated approach, the enterprise allocations as calculated by AgRE Calc were applied as a ratio through which gross emissions estimates were processed. To derive the emissions intensity, the annual beef enterprise footprint was divided by the beef LW sales, providing an emissions intensity estimate in kg CO_2-eq / kg beef LW.

3. Results and Discussion

3.1. Whole-Farm GHG Emissions

A total of 35 emissions estimates were calculated from the seven datasets and five tools. The data allowed complete footprints to be produced from each tool, with two partial exceptions, Firstly, CPLANv0 did not include embedded emissions estimates for any sources (Section 3.3.2). Secondly, the Cool Farm Tool required more detail than was available in the sample data in order to produce an estimate for woodland CO_2 sequestration (Section 3.3.4). Including CO_2 sequestration by woodland, results ranged from -6.67 (CALM Tool, Farm G) to 3.89 kt CO_2-eq y^{-1} (AgRE Calc, Farm A). Excluding sequestration, these totals ranged from 0.15 (CPLANv0, Farm G) to 4.02 (AgRE Calc, Farm A). Whilst this represents, to some extent, the actual variability in farms, a considerable amount is attributable to the tools themselves, and it is therefore notable that the range of estimated emissions between farms using the same calculator is comparable with the range of emissions on an individual farm using different calculators (Table 4).

Table 4. Gross farm-level GHG footprints (in kt CO_2-eq y^{-1}) as calculated by the five sample tools. Sequestration of CO_2 by woodland (negative) is not included in these totals.

Farm	AgRE Calc	Cool Farm Tool	CALM	CPLANv0	CFF Calculator	Mean	Range
A	4.02	2.92	2.99	0.77	3.01	**2.74**	**3.25**
B	2.69	2.82	2.49	0.64	2.84	**2.29**	**2.2**
C	3.53	2.29	2.61	0.75	2.58	**2.35**	**2.78**
D	3.36	2.4	1.94	0.35	2.16	**2.04**	**3**
E	1.93	1.87	1.59	0.42	1.51	**1.46**	**1.51**
F	1.98	1.61	1.63	0.56	1.91	**1.54**	**1.42**
G	0.61	0.47	0.42	0.15	0.53	**0.44**	**0.46**
Mean	**2.59**	**2.05**	**1.95**	**0.52**	**2.08**		
Range	**3.41**	**2.45**	**2.57**	**0.62**	**2.48**		

Even with results fully aggregated, it is apparent that some tools are following markedly different approaches to the process of farm-level GHG accounting (Fig. 1). The CPLANv0 tool appears consistently below the general trend. AgRE Calc produced the highest results on average. A partial grouping is apparent, with results from CALM, the Cool Farm Tool, the CFF calculator and, to some extent, AgRE Calc, following a similar pattern.

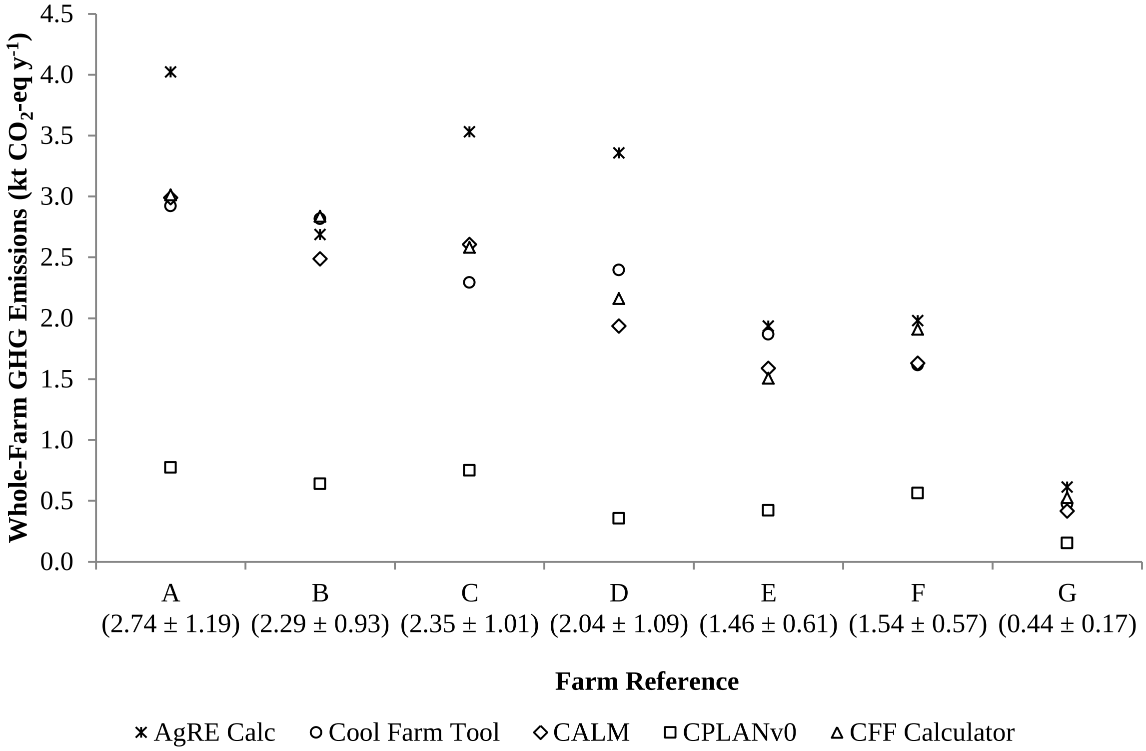

Figure 1. Total GHG footprints for each of the five calculators over the seven sample farms. Sequestration of CO_2 by woodland, deductible from the footprint, is excluded from the totals in this figure. The calculated mean estimate from the five tools ± 1 *S.D.* are shown in parentheses.

Tool variability was reasonably consistent relative to the magnitude of the estimate. Estimates for Farm D were somewhat more variable, however; a large pig enterprise dominates output for this farm (Table 3), implying higher levels of inconsistency in the way that emissions were calculated for this livestock type.

Between 5 and 14 (*Mdn* = 10, *N* = 35) individual sources made up the total emissions estimate for each farm. This highlights an issue inherent in farm-level footprinting; with every additional emission source included in the estimate, the number of potential causes for methodological variability in the final footprint increases accordingly.

As such, it is entirely possible for the composition of estimates to differ without affecting the final value of the farm-level footprint. The insight which can be gained by examining the footprints at farm-level is therefore limited, and to further explore the model methodology, the following sections examine these estimates at category level.

3.2. Livestock Emissions

Direct emissions from livestock represented the largest overall emissions category, contributing between 43% and 92% (M = 72%, N = 35) to the overall farm-level footprint. As such, emissions from this source are broken down into the two contributing subcategories (enteric and manure emissions) for analysis. Included in this assessment were estimates from all five tools, as well as manually calculated Tier I and II estimates (Fig. 2).

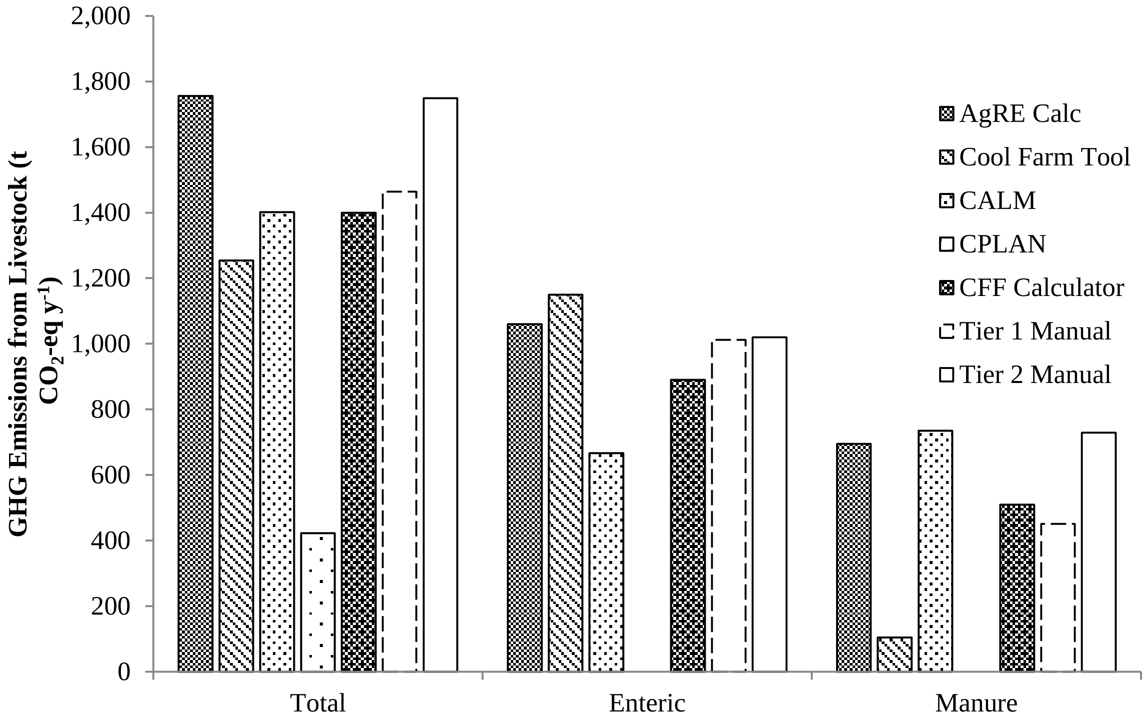

Figure 2. Graph showing mean livestock emissions estimates (n = 7) for each of the tools and manual calculations, including a breakdown into subcategories. The CPLANv0 calculator did not produce results at subcategory level and hence only the total is shown for this tool.

The Tier I and II manual calculations show consistent disparity across the sample farms. Tier I methodology gave lower total livestock emissions as compared to Tier II level calculations for the farms included in this study (Fig. 2). Further examination of results indicated that manually calculated Tier I estimates ranged from 74.7% – 98.6% of their Tier II counterparts (M = 84.5%, N = 7).

Examining the breakdown of these emissions into subcategories, it is clear that the difference between the Tier I and II methodology stems from the estimate of manure emissions (Fig. 2). One explanation for this lies in the fact that Tier I methodology employs activity data for manure management system usage which is generic to Western Europe. Manure management systems vary considerably, and so if this data does not accurately represent the sample farms, it could lead to the disparities shown here.

3.2.1. AgRE Calc

A close grouping can be observed between AgRE Calc and the manual Tier II calculations. For manure calculations, AgRE Calc differs from the manual Tier II approach in that it uses expert-supplied reference data to calculate the N content of manure (SRUC, 2014); this factor directly impacts N_2O emissions and can affect the total emissions substantially. This approach reduces data demand, an important consideration for farm-level tools. The close match to Tier II, for which N content was manually calculated, suggests that this is one area in which data demand may be reduced without unduly impacting results, though doing so limits the flexibility of the estimate.

3.2.2. The Cool Farm Tool

Hillier et al. (2011) followed IPCC (2006) Guidelines for the calculation of livestock emissions within the Cool Farm Tool, which is stated to perform at either a Tier I or Tier II level depending upon the availability of data. Sample data for all farms was sufficient to perform a Tier II estimate. Overall, however, results from the Cool Farm Tool undervalue livestock emissions as compared to the average totals for both Tiers of calculation (Fig. 2). This difference stems from the estimate for manure emissions. The Cool Farm Tool underestimates manure-related emissions as compared to both methodological Tiers, and to other tools. The reasons for this are unclear; given the methodological description by Hillier et al. (2011), the estimates would be expected to lie close to the Tier II manual estimates.

The relative contributions from subcategories to the livestock total are, for this tool, in stark contrast to other methodologies; at the livestock category and whole farm level, however, the Cool Farm Tool does not differ substantially (Figs. 1 and 2). Whilst the total result is unaffected, this means that the Cool Farm Tool would be likely to respond differently to changes in the livestock system, as compared to other tools.

3.2.3. The CALM Tool

Total livestock emissions as estimated by the CALM tool are similar to the manual Tier I calculations (Fig. 2). However, further breakdown reveals that the CALM Tool underestimated enteric emissions as compared to both Tiers. By contrast, the CALM tool's estimate of manure emissions was similar to Tier II. One possible explanation for this is that the CALM tool, though using a Tier I emission factor, calculates emissions based on farm-specific activity data. This may have captured some variability in manure emissions missed by the manual Tier I approach.

The CALM Tool was the only model to estimate, on average, higher manure-related emissions as compared to enteric emissions, apparently through underestimation of the latter. While methodology behind this is unclear, the response of the CALM calculator to livestock system changes would likely different to other tools for this reason.

3.2.4. CPLANv0

Total emissions as estimated by the CPLANv0 calculator fell starkly below those of all other tools and both manual calculations (Fig. 2). This is result is striking given the statement by the tool developers that the CPLANv0 tool follows IPCC (2006) methodology throughout (SEE360, 2007). The CPLANv0 tool presented results in highly aggregated format, and as such it was not possible to derive a breakdown for the livestock emissions category, hindering further speculation as to the methodology employed.

3.2.5. The CFF Calculator

The CFF calculator produced an average total emissions estimate which did not differ greatly from the Tier I methodology. Further examination of the breakdown of this estimate would suggest that the methodology closely mirrors the approach taken by the manual Tier I calculation.

The CFF Calculator produced results for manure which did not differ substantially from the Tier I manual calculation. This is surprising in that Whittaker et al. (2013) state that the only source of N_2O included by the CFF tool is crop residues, implying that N_2O is neglected in the estimate of manure emissions. It is difficult to confirm this explanation, as the tool does not provide results disaggregated by gas. It is plausible that an update has taken place since the study by Whittaker et al. (2013). Lack of methodological transparency such as this makes it difficult to predict how a tool will react to system changes.

3.3. Emissions from Other Sources

Emissions from sources other than livestock were assessed in the following categories, defined as 1) Land and Crops, 2) Embedded Emissions, 3) Fuels, and 4) Sequestration. Note that the fuels category includes emissions from electricity production and fossil fuel extraction, in addition to direct emissions. The average estimates for these categories are presented graphically in Fig. 3.

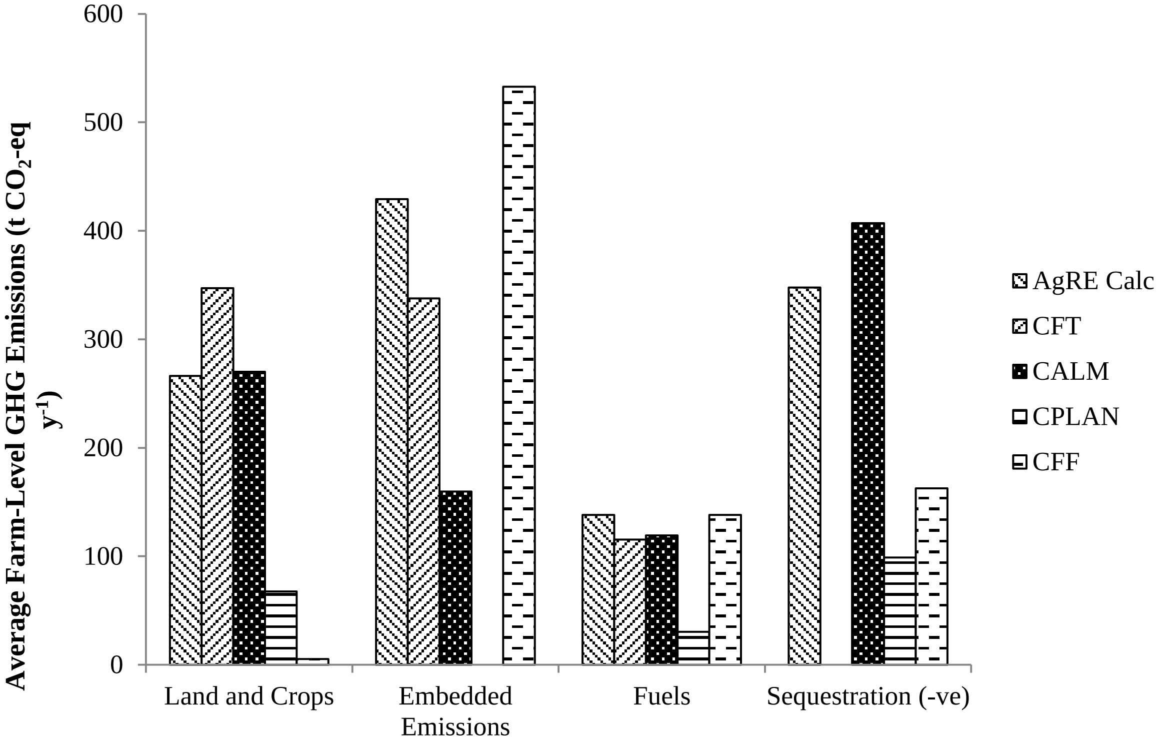

Figure 3. Average emissions for the seven sample farms, disaggregated by source category, as calculated by each tool.

3.3.1. Land and Crops

Emissions estimates were found to be highly variable for the Land and Crops category. In contrast to the low result produced by the Cool Farm Tool for manure emissions, the emissions estimate from land and crops exceeded that of all other calculators (m = 347,224 kg CO_2-eq y^{-1}). In comparison to the Tier I methodology employed by AgRE Calc and the CALM tool, the Bouwman et al. (2002) model employed by the Cool Farm Tool appears to have predicted slightly higher emissions than the IPCC methodology. Whilst the reasons for this are unclear, the Bouwman model captures greater variability in soil conditions than the Tier I approach, which may explain the difference in emissions.

Markedly lower than the general grouping were estimates by CPLANv0 and the CFF Calculator. For CFF Calculator, this difference is explicable, as the tool excludes all sources of N_2O emission with the exception of crop residues (Whittaker et al., 2013). This omission is substantial, with the mean land and crop estimate from the CFF Calculator (m = 5.19 t CO_2-eq y^{-1}) only 2.7% of the value of the mean estimate across all other tools (m = 191.24 t CO_2-eq y^{-1}).

The CFF Calculator estimates embedded emissions at a level much higher than the general grouping. It is possible that some of the 'missed' N_2O emissions are incorporated into this category, though without further methodological information or disaggregation of results it is not possible to confirm this speculation.

These omissions are likely to affect how the CFF Calculator responds to mitigation options designed to reduce N_2O emissions from land and crops. Optimisation of fertiliser application (and avoidance of over-applying) has been found to be a viable and cost-effective mitigation measure (Domingo et al., 2014); through excluding of this source of N_2O, the CFF Calculator would underestimate the effects of this.

It is unclear as to why results from the CPLANv0 calculator were consistently lower than the general grouping; the information supplied by the developers appears to suggest that the methodology follows IPCC (2006) Guidelines. Impeding further investigation is the fact that results from this tool are not disaggregated by source category.

3.3.2. Embedded Emissions

Estimates of embedded emissions varied considerably, and were the largest emissions category after livestock (Fig. 3). The CPLANv0 calculator was exempted from this assessment, as it did not appear to consider embedded emissions from any sources, though a lack of disaggregation of results made it difficult to ascertain this in the case of fertiliser.

Differences of scope between tools can explain a large amount of this variation (Table 2). Where possible, the scope was determined from information supplied by the tool developers; however, it was frequently necessary to infer this information from data input requirements. Consistent scoping of farm-level tools, particularly in the context of embedded emissions, represents a challenge for developers. These results make it clear that until such a consensus is reached, is important for users to be aware of the impacts this can have on total estimates.

3.3.3. Fuels

Whilst showing some variation, emissions estimates were relatively consistent between tools, with the exception of CPLANv0, which markedly underestimated by comparison (Fig. 3). Except to note that low estimates appear to be typical of the CPLANv0 tool, it is difficult to ascertain why this may be, as the developers did not state which methodology was applied.

For the Cool Farm Tool and AgRE Calc however, the methodology used to compute emissions from this source is known; Hillier et al. (2011) state that the Cool Farm Tool uses and EcoInvent database (Ecoinvent Centre, 2007), whilst AgRE Calc uses the publicly available DEFRA/DECC (2011) Emission Factors for Company Reporting (SRUC, 2014). These tools provided similar average estimates, whilst the CALM Tool and CFF Calculator provided estimates which, though of uncertain provenance, were consistent with the group trend.

It is worth noting that the fraction of farm-level emissions stemming from fossil fuel use is not high, varying from 2.5 to 11.0% of the net total emissions for the sample farms (M = 6.2%, N = 35). Consequently, where variability in estimates for this category is minor, it is unlikely to markedly affect the overall total.

3.3.4. CO_2 Sequestration

Before examining tool results for CO_2 sequestration, it should be acknowledged that the benefits of carbon sequestration by woodland as an approach to offset farm-level GHG emissions are the subject of complex debate (Cannell, 1999) and ongoing research (Feliciano et al., 2013). Whilst the full extent of this debate falls outside the scope of the present study, it is considered here as this component of the GHG footprint is universally included by the present sample of tools.

Estimates made by the tools for CO_2 sequestration also showed considerable disparity (Fig. 3). Some explanation for this disparity may well lie in the number of methodologies available to calculate sequestration by woodland, with methodologies provided by the US Forest Service, UK Forestry Commission as well as the IPCC (2006) Guidelines. The latter has been adopted by both AgRE Calc and the CALM tool.

As a global methodology, the IPCC (2006) Guidelines supply limited data for temperate woodlands. Estimates of sequestration from AgRE Calc (m = 405.7 t CO_2 y^{-1}, n = 7) and the CALM tool (m = 474.8 t CO_2 y^{-1}, n = 7) exceed others by a considerable margin; it may be that the lack of data has led to generalisations which overestimate CO_2 sequestration as compared to other methodologies. Comparison with an estimate manually produced for the seven farms using the (UK-specific) Forestry Commission's Carbon Lookup Tables (West and Matthews, 2012) (m = 269.2 t CO_2 y^{-1}, n = 7), falls closer to the lower estimates from other tools, supporting this speculation.

The CFF Calculator produced the median estimate for this category (Mdn = 189.6 t CO_2 y^{-1}); whilst this value is somewhat lower than the Forestry Commission-derived estimate, the references given for the tool (CFF, 2012) suggest that this source was used by the developers. This being the case, the disparity between the manually calculated estimates (m = 269.2 t CO_2 y^{-1}) and the results of the CFF Calculator (m = 189.6 t CO_2-eq y^{-1}) demonstrates the consequence of differing interpretations of this methodology.

The Cool Farm Tool's sequestration assessment required input of species composition and trunk diameter change over a one-year period. The available data did not allow for this level of detail, and assumptions made in this respect can significantly influence results. As such, comparison to other tools would have limited validity, and the decision was made to avoid producing a potentially misleading estimate. Users of the Cool Farm Tool without access to specialist forestry data would face a similar decision.

The sequestration estimate of the CPLANv0 tool, whilst low, was higher in relative terms compared to its estimates for other emissions sources. Thus, the balance of emissions vs. sequestration reported by this tool is likely to differ in comparison to other tools. Where sequestration is used to offset emissions from other parts of a farming system, this difference will substantially affect how that system is seen to perform.

Several tools went into greater depth in this area than could be explored using the sample data. The Cool Farm Tool has the ability to assess emissions/sequestration from land use change (LUC) for up to a maximum of 20 years, as well as changes in tillage practice and use of cover crops. The CFF Calculator considers sequestration not only from woodland, but also from single trees, hedges, field margins, orchards, vineyards, soil and wetlands. The CPLANv0 tool has the facility to assess emissions/sequestration from LUC since the year 1957 in addition to forestry. Finally, whilst the CALM calculator limits its approach to woodland, it includes the facility to assess managed woodland in detail according to species, age and management strategy. Whilst it was not possible to empirically assess the effect of these differences in scope using the sample data, it is certain that the output would be affected. This difference may be substantial, depending upon the extent of these features in a given system.

3.4. Emissions Intensities and Allocation

GHG emissions intensities for beef production, in kg CO_2-eq kg beef LW^{-1} were calculated for each farm (*n* = 7) and each tool (*n* = 5) as described in Section 2.3, creating a total of 35 estimates.

The mean emissions intensities calculated by the tools (Fig. 4) show some similarity to those published in LCA literature. It is important to note that the LCA estimates shown are based on studies of a range of systems and scales and so direct comparisons should be made with extreme caution; however, broadly speaking this similarity does appear to indicate some consistency in approach between LCA practitioners and developers of these farm-level models.

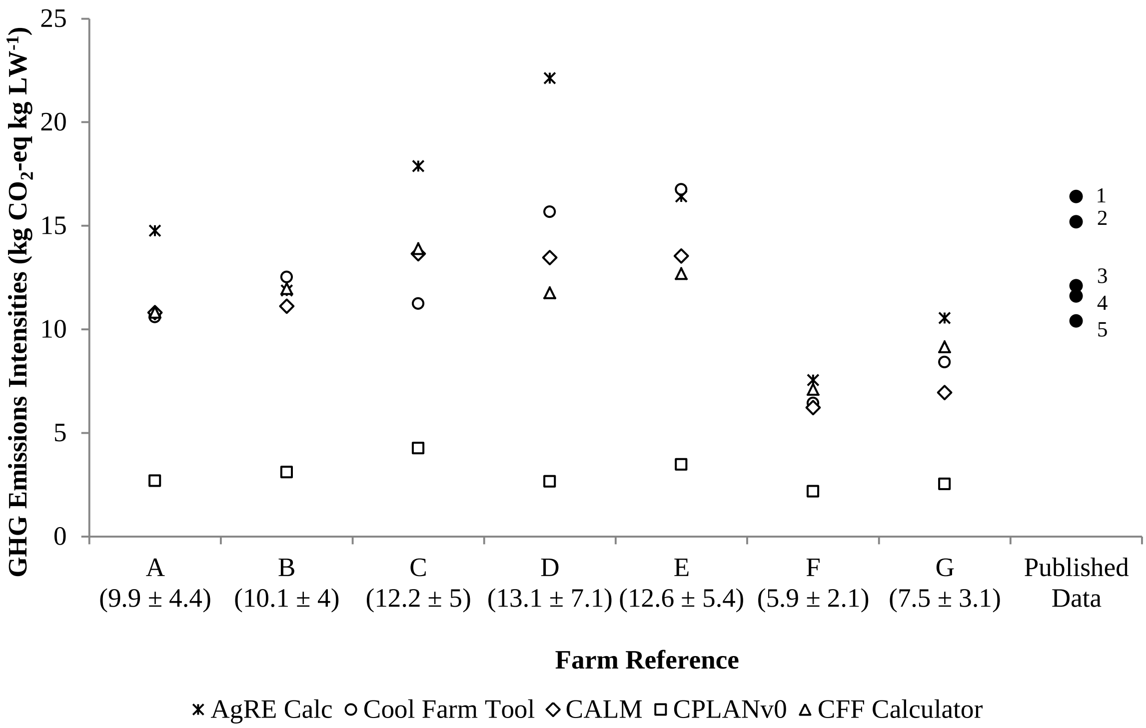

Figure 4. Emissions intensities calculated for each farm and tool (*N* = 35). The calculated mean estimate from the five tools ± 1 *S.D.* are shown in parentheses. Emissions intensities from a range of published LCA literature are shown in the final column, for which the sources are 1) Nguyen et al. (2012) (a calculated average from four systems); 2) Vergé et al. (2008); 3) Beauchemin et al. (2011); 4) Vergé et al. (2008); and 5) Casey and Holden (2006). For values 1) and 3), a conversion

factor of 1/0.55 (Opio et al., 2013) was applied to convert the published values from kg Carcass Weight (CW) to kg Live Weight (LW).

Farm D showed the greatest mean emissions intensity (m = 13.1 ± 7.1 kg CO_2-eq kg LW^{-1}), though this was not markedly larger than the highest published values. It is likely that the magnitude of this estimate is a result of the intensive nature of this farming system. The high variability in estimates for this farm is likely to stem from the large pig unit present in the system; when assessing the whole-farm estimates (Section 3.1) it was noted that the tools varied considerably in the estimates produced for this enterprise. More generally, a higher range for the emissions intensity appears to correspond to systems showing a more complex array of enterprise types.

The relatively low mean estimate for Farm F (m = 5.9 ± 2.1 kg CO_2-eq kg beef LW^{-1}) is likely to stem from the fact that the main output for this farm is a dairy enterprise, the offspring from which are retained and finished for beef. This is not directly comparable with the published values (Fig. 4), which relate to dedicated beef systems. Here, the majority of emissions from breeding animals are associated with the dairy enterprise, and the system avoids the overheads present in a typical suckler system. Farm G (m = 7.5 ± 3.1 kg CO_2-eq kg beef LW^{-1}) is a typical suckler system; emissions from this enterprise are low due to an avoidance of inputs such as fertiliser and pesticides. As a consequence of this, the tools which produced the highest results for this farm were those which, on average, attributed the greatest values to enteric emissions estimates (AgRE Calc, CFF and the Cool Farm Tool). The estimates of these tools were comparable to the lower bounds of the published data (Fig. 4).

The CPLANv0 tool consistently forms the lower bound of estimates. The average emissions intensity, as calculated by this tool across the enterprises (m = 3.0 kg CO_2-eq kg beef LW^{-1}, n = 7) falls far below any of the published values shown in Fig. 4, indicating a significant methodological disparity between the CPLANv0 tool and these studies. AgRE Calc typically forms the upper bound of estimates; this is likely due to a number of factors identified thus far. Use of IPCC (2006) Tier II level methods for calculation of direct livestock emissions is likely to have increased this part of the estimate above those tools which follow Tier I methodology. Additionally, AgRE Calc was shown to have the broadest scope for the embedded emissions sources present in the sample datasets; thus, inclusion of these likely further increased the estimate beyond other tools. The Cool Farm Tool, the CALM Tool and the CFF Calculator are generally relatively closely grouped, though the order of this grouping varies somewhat between farms (Fig. 4). In neglecting major sources of N_2O from the estimate, the CFF Calculator is relatively low for farms where N fertiliser use is high (e.g. Farms D and E), though high estimation of the magnitude of embedded emissions may counter this to some extent. Where enteric emissions make up a higher proportion of the total, the CALM Tool appears to fall below the general grouping due to the lower emphasis it places on this emissions source (e.g. Farm G).

4. Conclusions

The broad range of sample data allows for some consideration of tools' fitness-for-purpose in the context of footprinting livestock systems. In the absence of an accepted, harmonised methodology for farm level tools, this conclusion avoids making explicit recommendations on tool fitness-for-purpose, but seeks to explore possible criteria for this in the light of tools' performance on real-world livestock enterprises.

4.1. Tool transparency

In any such application, transparency of tool methodology is an important consideration, accounting for inevitable variation and allowing informed comparisons to be made. A lack of transparency in methodology was found to be a major issue for several tools, limiting the insights which could be gained. Hillier et al. (2011) took steps to address this through publication in the case of the Cool Farm Tool, though in some cases it remains unclear what method is being followed. Developers of the CALM Tool and CFF Calculator provided some information on methodology, though lack of detail made it difficult to assess exactly how results were calculated. Developers of the CPLANv0 tool stated that IPCC (2006) Guidelines were used but gave no further information as to additional sources of methodology. Seeking to address this issue for AgRE Calc, methodological sources for this tool are presented for the first time in this paper (Section 2.1.1). Methodological transparency and availability of information is likely to be a key concern where these tools are sought to inform policy (Hall et al., 2010), and hence is a potential limiting factor in the uptake of tools by policy makers. It may also limit the extent to which users can employ the tools make informed decisions on mitigation of emissions from farming systems.

4.2. Tool methodology

Studies have demonstrated the importance of nitrous oxide emissions from cultivation of palm oil and sugar cane (Keller et al., 2014), wheat (Whittaker et al., 2013), and several additional cereal cultivation scenarios (Lewis et al., 2013). This study shows the same is true in the case of livestock systems, not least because such systems are likely to feed the livestock enterprise. Estimates of land and crop emissions by the CALM tool, the Cool Farm Tool and AgRE Calc showed reasonable parity in the results, whilst those of CPLANv0 and the CFF tool were considerably lower. In the case of the CFF tool it is known that the developers omitted several sources of N_2O (Whittaker et al., 2013), which accounts for the low estimate; for the CPLANv0 tool, the reason for this is not known since IPCC methodology is stated to have been followed. Users should be aware that omissions or underestimation of this emissions source may significantly affect the size of the overall footprint. Additionally, where these tools are employed as decision aids for measures aimed to reduce N_2O emissions, the efficacy of such approaches may be underestimated.

Estimates of emissions from livestock and manure showed reasonable parity between tools, with the exception of CPLANv0, which again markedly underestimated. Results from the study data show this to be the largest emissions source with the potential to significantly impact results if inconsistently handled. Calculated emissions from manure showed most variability within the category; not all of this was explicable with the available information, and may be due to differing interpretations of the IPCC (2006) guidelines and manure storage categories. The Cool Farm Tool (Hillier et al., 2011) showed the most notable difference in this area. The implications of this are important for users to recognise, given that manure has been shown to offer considerable mitigation potential both in terms of diet (Mathot et al., 2012) and storage management (Masse et al., 2008). Where it is unclear precisely how these emissions are calculated, users should be wary of employing tools to estimate the efficacy of related mitigation measures.

Calculation of embedded emissions (emissions from production of agrochemicals and feeds) varied considerably and in some cases represented the second largest emissions category behind livestock.

The differing scopes of assessment for this category (section 3.3.2) appear to be largely responsible for these differences. Harmonisation of tool methodologies in this respect should be a key aim for those with development oversight, and users should be aware of the impact such disparities can have on the footprint. Crucially, in the context of decision-making for cleaner production, omission by some tools of certain embedded emission sources may lead to false economies through uneven consideration of trade-offs.

Emissions from fuel and electricity, as estimated, were relatively consistent between tools, again with the exception of CPLANv0. As the smallest emission category, it appears the slight differences present here are not of great concern to tool users, though as with embedded emissions, the consideration of this category may be important to prevent false economies of mitigation.

Considerable variation, reflective of disparity in the methodologies employed, was present in the estimation of CO_2 sequestration. In particular, the IPCC (2006) methodology, as applied by two tools, appears to be insufficient to account for much variation in British woodlands, and overestimates CO_2 sequestration at least with respect to other, country-specific methodologies. The issue of variable methodologies is exacerbated given that the efficacy of GHG offset through biomass sequestration is not clear-cut (Cannell, 1999), and the complex nature of this component is at odds with its simplistic "positive vs. negative" representation in the tools. Further complication may be added where these woodlands are actively managed (Proietti et al., 2016). In the context of biomass sequestration as a means to promote cleaner production, such simplification is a very important consideration for tool users and policy makers to be aware of. For the tools, a level of consensus on both the scope of assessment for CO_2 sequestration, and on the methodology employed, would be advantageous.

Finally, it is worth noting that no tools provide estimates of uncertainty alongside the footprints produced. From a scientific standpoint, simplistic GHG modelling such as this carries significant uncertainty; however, this is complex to calculate and interpret, and may not be relevant to the aims of many users. However, it is important to be aware, particularly if tools are employed to guide policy decisions, that even where methodology is transparent, estimates nonetheless carry a degree of uncertainty.

4.3. Allocation within tools

For benchmarking applications, or to facilitate comparisons between farms, it becomes necessary convert the farm-level estimate into a standardised functional unit (e.g. kg CO_2-eq / kg product). Allocation of emissions is a key issue in this respect, with complexity of typical livestock systems amply demonstrated by the sample data. Cropping enterprises footprinted by previous tool reviews considered only single-output enterprises and hence did not encounter this issue.

In more complex systems, where a farming system produces more than one product type, tool users must allocate emissions between enterprises in order to separate the product footprints. This may be beyond the skills of an average user, and decisions made at allocation stage have been shown to significantly affect results (Nguyen et al., 2012); thus, it is advantageous that it be performed according to standardised, transparent methodology by the tool itself. Since cleaner production aims are likely to focus on product emissions intensity, rather than farm-level footprint, the ability to consistently separate footprints for mixed enterprises is important. Those with oversight on tool development should be aware of this requirement, and users should be aware of this issue where tools are used to inform decisions or policy. Whilst the requirement to allocate is recognised by some tool developers, the only tool in the current sample with the capability to perform this operation was AgRE Calc.

4.4. Final summary

It has been well recognised that the broad scope of farm-level tools such as these represents a considerable strength (Schils et al., 2007), and their performance in the context of this assessment exemplifies this; however, to obtain this advantage requires the compilation of a broad range of methodologies. This study highlights the hazards associated with such an approach, particularly where tool transparency is lacking. Previous reviews have highlighted, in the context of crop production, the requirement to harmonise tool methodology for consistency in results. This study backs that conclusion in the context of livestock enterprises, and the conclusions presented herein provide a decision aid for users to select an appropriate tool for their required purpose. This study additionally finds that even where estimates appear consistent, variation in the component parts of an estimate may exist independently of variation in the whole. Tools may therefore react differently to changes in the modelled system, and as a result should be used with caution to inform mitigation strategies.

It is important that users of farm-level tools acknowledge these issues and treat results with appropriate caution. Where a tool is sought to assist in the derivation or assessment of cleaner production aims, or for the purpose of influencing or informing policy decisions (e.g. Hall et al., 2010), it is vitally important that variation be accounted for, and that areas of opacity in methodology be recognised. Whether prospective tool users are primary producers or policy makers, this study provides a reference point for tool selection and use. Similarly, it provides a synthesis of the state of the art which will be of use to developers in furthering these tools in their ability to provide consistent environmental assessment and decision support for cleaner agricultural production.

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